

Dijet induced collective modes in an anisotropic quark-gluon plasma

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We discuss the collective modes due to the propagation of two oppositely moving relativistic jets (dijet) in an anisotropic quark-gluon plasma (AQGP) and compare the results with the case of single jet propagation. For the sake of simplicity, assuming a tsunami-like initial jet distribution, we observe that the dispersion relations for both the stable and unstable modes are altered significantly due to the passage of dijet in comparison with the case of single jet propagation. It has been further demonstrated that the growth rate of instability, due to introduction of dijet in the system, increases compared to the case of single jet case. As in the case of single jet propagation, the instability always grows when the jet velocity is perpendicular to the wave vector. We, thus, argue that the introduction of dijet in the AQGP, in general, leads to faster isotropization than single jet propagation.

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I. INTRODUCTION

One of the goals of the ultra-relativistic heavy-ion collision experiments at BNL RHIC and at CERN LHC is to produce a deconfined state of QCD matter commonly known as quark gluon plasma (QGP). The properties of such a system, if formed, can be studied through various probes such as electromagnetic probe, jet quenching etc.. According to QCD thermodynamics studied on lattice, this novel state of matter is expected to be formed at temperatures of the order of $T \sim 170 - 200 \text{ MeV}$. The jet of particles produced initially due to hard collision, when passes through such a system loses energy and results in decrease of high energy hadrons produced due to the jet fragmentation. This phenomenon is commonly known as jet quenching. Moreover, the passage of jets influences the collective modes of the system [1–5].

The effect of single jet propagation on the plasma collective modes has been studied in Refs [1–3] where it has been assumed that the plasma is isotropic in momentum space and the jet is described by a tsunami-like jet distribution. In a very recent work the present authors have relaxed the condition of isotropic QGP and studied the characteristics of both stable and unstable collective modes of AQGP due to the passage of relativistic jet using transport theory [4]. It is shown [4] that the dispersion relations are modified quite substantially in comparison to the no jet case. On the other hand, the authors of Ref [5], have investigated the dijet induced properties of the unstable modes in isotropic QGP. Also the energy loss due to stream instabilities induced by dijet has been discussed using both tsunami-like and Gaussian distributions for the relativistic jets within the same approach as in Refs. [1–4]. We extend the work of Ref. [4, 5] to AQGP and study the characteristics of both stable and unstable

modes due to the passage of two jets moving in opposite direction. It should be noted that non-equilibrium jet of particles while travelling through QGP disturbs the plasma exciting chromomagnetic and chromoelectric modes of which some of modes might even be unstable. The most important among those are the modes which grow exponentially in time. Plasma instabilities due to jet propagation in AQGP have been the subject of extensive studies as when the instability occurs, the kinetic energy of the particles is converted to the field energy leading to faster isotropization [6–9] of the QGP. This type of phenomenon occurs if it is assumed that the hadronization time is greater than the time to generate the growth of the gauge fields. For the complete development of plasma instabilities, the time scale should be of the order of $t \sim (6.7 - 12.5)/\omega_t$, where ω_t is the total angular frequency of the whole system [2, 3].

We use the same simplifying assumptions as in Ref. [2–5] to study the stable and unstable modes of AQGP induced by two counter propagating jets and compare it with that obtained in case of single jet [4] and no jet case [10, 11]. AQGP is realized in the very early stages of heavy-ion collision due to rapid longitudinal expansion. As a consequence, the cooling is faster in the longitudinal direction which results in $\langle p_L^2 \rangle \ll \langle p_T^2 \rangle$. Such momentum-space anisotropy modifies the collective modes which have different behavior in comparison to that in isotropic QGP (see Refs. [10, 11] for details). Due to the passage of relativistic jets in a non-equilibrium plasma, with an anisotropic distribution in momentum space, the behavior of collective modes change as will be demonstrated in the following.

The essential ingredient to study the collective modes in the composite system (AQGP+jets) is the transport equation which reduces to Vlasov equations for the time scale shorter than the mean free path time [6, 12]. In our calculation we assume (i) weak coupling regime i.e. $g \ll 1$ and (ii) the interactions between jet and plasma is only mediated by mean gauge fields. The interactions between the jet particles and the plasma particles leads

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kinetic instability initiated either by charge or current fluctuations which lead to electric and magnetic instabilities. The latter is also known as Weibel instability [13]. It has been demonstrated in Ref. [10, 11] that the growth rate of magnetic instability is maximum in the direction of anisotropy in momentum-space anisotropic plasma. So while studying the characteristics of the unstable modes we assume that the momentum of the collective mode is in the direction of the anisotropy.

The organization of the paper is as follows. In section 2 we mention the required formalism very briefly as detail has already been presented in [2–5]. In section 3 results for both stable and unstable modes will be presented followed by summary in section 4.

II. FORMALISM

To study the jet induced collective modes in AQGP we dwell on the transport theory described in detail in Ref. [2–5]. For the sake of simplicity, we assume two jets propagating in opposite direction described by the following tsunami-like distribution [3]

$$f_{jet}(\mathbf{p}) = \bar{n} \bar{u}^0 \delta^{(3)}(\mathbf{p} - \Lambda \bar{\mathbf{u}}). \quad (1)$$

Here \bar{n} is related to the density of the plasma and \bar{u}^μ is the four-velocity. The parameter Λ fixes the scale of energy of the particles. More realistic distribution, such as, a Gaussian distribution can be used to simulate the same effect [5].

Using Vlasov approximation one can write down the polarization tensor for particles species α as [2, 3, 10, 15]:

$$\Pi_\alpha^{\mu\nu}(k) = g^2 \int_p p^\mu \frac{\partial f_\alpha(\mathbf{p})}{\partial p^\beta} \left(g^{\beta\nu} - \frac{p^\nu k^\beta}{p \cdot k + i\epsilon} \right) \quad (2)$$

where α specify the quarks, antiquarks, gluons or partials of jet. The polarization tensor is symmetric, i. e. $\Pi^{\mu\nu}(k) = \Pi^{\nu\mu}(k)$, and transverse, $k^\mu \Pi^{\mu\nu} = 0$.

We assume that the ansatz for the anisotropic momentum distribution is given by [10, 11]:

$$f(\mathbf{p}) = f_\xi(\mathbf{p}) = N(\xi) f_{iso}(\sqrt{\mathbf{p}^2 + \xi(\mathbf{p} \cdot \hat{\mathbf{n}})^2}). \quad (3)$$

Here f_{iso} is the distribution function in isotropic case. $N(\xi)$ is the normalization constant which is equal to $\sqrt{1+\xi}$, $\hat{\mathbf{n}}$ is the unit vector along the direction of anisotropy. The anisotropy parameter ξ lies in the range $-1 < \xi < \infty$. Using the above ansatz the spacelike component of the self-energy tensor can be written as (from Eq.(2)):

$$\Pi_p^{ij}(k) = m_D^2 \sqrt{1+\xi} \int \frac{d\Omega}{(4\pi)} \frac{v^l + \xi(\mathbf{v} \cdot \hat{\mathbf{n}}) n^l}{(1 + \xi(\mathbf{v} \cdot \hat{\mathbf{n}})^2)^2} \left(\delta^{jl} + \frac{v^j k^l}{(k \cdot v + i\epsilon)} \right) \quad (4)$$

where

$$m_D^2 = -\frac{g^2}{2\pi^2} \int_0^\infty dp p^2 \frac{df_{iso}(p^2)}{dp} \quad (5)$$

is the isotropic Debye mass. Since the self energy depends on the four-momentum(k^μ) and the anisotropic vector ($n^\mu = (1, \hat{\mathbf{n}})$), it can be decomposed in a suitable tensorial form in a covariant gauge [10, 16]:

$$\Pi_p^{ij}(k) = \alpha A^{ij} + \beta B^{ij} + \gamma C^{ij} + \delta D^{ij} \quad (6)$$

where

$$A^{ij} = \delta^{ij} - k^i k^j / \mathbf{k}^2, \quad (7)$$

$$B^{ij} = k^i k^j / \mathbf{k}^2, \quad (8)$$

$$C^{ij} = \tilde{n}^i \tilde{n}^j / \tilde{n}^2, \quad (9)$$

$$D^{ij} = k^i \tilde{n}^j + k^j \tilde{n}^i, \quad (10)$$

where $\tilde{n}^i = A^{ij} n^j$ which obeys $\tilde{\mathbf{n}} \cdot \mathbf{k} = 0$ and the structure functions α, β, γ and δ can be obtained by appropriate contractions (see [10, 16] for details). In the limit of $\xi \rightarrow 0$, (isotropic case) γ and δ vanish whereas, α and β are directly related to the transverse and longitudinal components of the polarization tensor of the plasma respectively.

In a similar way, the polarization tensors induced by the jets (moving in opposite direction) with the tsunami-like momentum distribution can be calculated to obtain the following expressions [5]:

$$\Pi_{jet1}^{ij}(k) = -\omega_{jet}^2 \left(\delta^{ij} + \frac{k^i v_{jet}^j + k^j v_{jet}^i}{\omega - \mathbf{k} \cdot \mathbf{v}_{jet}} - \frac{(\omega^2 - \mathbf{k}^2) v_{jet}^i v_{jet}^j}{(\omega - \mathbf{k} \cdot \mathbf{v}_{jet})^2} \right), \quad (11)$$

$$\Pi_{jet2}^{ij}(k) = -\omega_{jet}^2 \left(\delta^{ij} - \frac{k^i v_{jet}^j + k^j v_{jet}^i}{\omega + \mathbf{k} \cdot \mathbf{v}_{jet}} - \frac{(\omega^2 - \mathbf{k}^2) v_{jet}^i v_{jet}^j}{(\omega + \mathbf{k} \cdot \mathbf{v}_{jet})^2} \right), \quad (12)$$

where v_{jet} is the velocity of jet and $\omega_{jet}^2 = \frac{q^2 \bar{n}}{2\Lambda}$ is the plasma frequency of the jet. Moreover, the polarization tensors due to the jets can be decomposed in the following way:

$$\Pi_{jet1}^{ij} = \alpha' A^{ij} + \beta' B^{ij} \quad (13)$$

$$\Pi_{jet2}^{ij} = \alpha'' A^{ij} + \beta'' B^{ij} \quad (14)$$

where

$$\alpha' = -\frac{\omega_{jet}}{2} \left[2 - \frac{\omega^2 - k^2}{(\omega - k v_{jet} \cos \theta_{jet})^2} v^2 \sin^2 \theta_{jet} \right] \\ \beta' = \omega_{jet}^2 \omega^2 \frac{v^2 \cos^2 \theta_{jet} - 1}{(\omega - k v_{jet} \cos \theta_{jet})^2} \quad (15)$$

$$\alpha'' = -\frac{\omega_{jet}}{2} \left[2 - \frac{\omega^2 - k^2}{(\omega + k v_{jet} \cos \theta_{jet})^2} v^2 \sin^2 \theta_{jet} \right] \\ \beta'' = \omega_{jet}^2 \omega^2 \frac{v^2 \cos^2 \theta_{jet} - 1}{(\omega + k v_{jet} \cos \theta_{jet})^2}. \quad (16)$$

For numerical convenience, we introduce another parameter η defined by $\eta = \omega_{\text{jet}}^2 / \omega_t^2$ where $\omega_t^2 = \omega_{\text{jet}}^2 + m_D^2/3$.

In the analysis of the collective modes of the composite system we are interested in very short time scales where the collisionless approximation is justified. The effect of jet of particle is to induce the color fluctuations, which provide a contribution to the polarization tensor of the system. According to the linear response theory, the total polarization tensor of the whole system is given by the sum of polarization tensors of the plasma and the two jets. Thus we have,

$$\Pi_t^{\mu\nu}(k) = \Pi_p^{\mu\nu}(k) + \Pi_{\text{jet1}}^{\mu\nu}(k) + \Pi_{\text{jet2}}^{\mu\nu}(k) \quad (17)$$

The dispersion relation of the collective modes of the total system can be determined by solving the equation

$$\det[(k^2 - \omega^2)\delta^{ij} - k^i k^j + \Pi_t^{ij}(k)] = \det[\Delta^{-1}(k)]^{ij} = 0. \quad (18)$$

where, in the temporal axial gauge, the effective propagator Δ^{ij} is given by,

$$\Delta^{ij}(k) = \frac{1}{[(k^2 - \omega^2)\delta^{ij} - k^i k^j + \Pi_t^{ij}(k)]}. \quad (19)$$

Therefore, using Eqs.(6), (11), (12), and (17) the effective propagator of the composite system can be written as

$$\Delta(k) = \Delta_A \mathbf{A} + (\mathbf{k}^2 - \omega^2 + \alpha + \alpha' + \alpha'' + \gamma) \Delta_G \mathbf{B} + [(\beta + \beta' + \beta'' - \omega^2) \Delta_G - \Delta_A] \mathbf{C} - \delta \Delta_G \mathbf{D} \quad (20)$$

with

$$\Delta_A^{-1} = \mathbf{k}^2 - \omega^2 + \alpha + \alpha' + \alpha'', \quad (21)$$

$$\Delta_G^{-1} = (\mathbf{k}^2 - \omega^2 + \alpha + \alpha' + \alpha'' + \gamma)(\beta + \beta' + \beta'' - \omega^2) - \mathbf{k}^2 \tilde{n}^2 \delta^2. \quad (22)$$

III. RESULTS

A. Stable modes

The collective modes of the system comprising of the plasma and the jets are obtained by finding the zeros of Eqs. (21) and (22). For real values of $\omega > |\mathbf{k}|$, the dispersion relation for A -modes can be determined by finding the solutions of the equation:

$$\omega_A^2 = \mathbf{k}^2 + \alpha(\omega_A) + \alpha'(\omega_A) + \alpha''(\omega_A) \quad (23)$$

In case of G -modes we factorize Δ_G^{-1} as

$$\Delta_G^{-1} = (\omega^2 - \omega_{G+}^2)(\omega^2 - \omega_{G-}^2) \quad (24)$$

where

$$\omega_{G\pm}^2 = \frac{1}{2}(\bar{\omega}^2 \pm \sqrt{\bar{\omega}^2 + 4\mathbf{k}^2 \tilde{n}^2 \delta^2}), \quad (25)$$

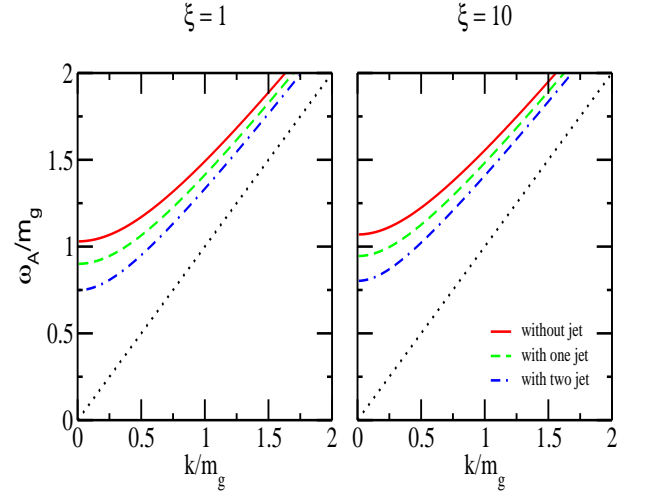


FIG. 1: (Color online) The dispersion relation for the stable A -mode for an anisotropic plasma with jet for different values of the anisotropy parameter $\xi = \{1, 10\}$, $\eta = 0.2$, $\theta_{\text{jet}} = 0$, $v_{\text{jet}} = 0.7$ and $\theta_n = 0$

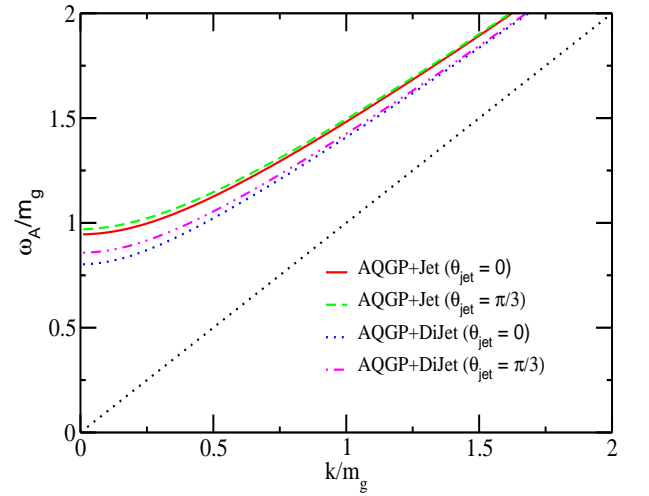


FIG. 2: (Color online) The dispersion relation for the stable A -mode for the system composed of anisotropic plasma with single jet and dijet for $\xi = 10$, $v_{\text{jet}} = 0.7$, $\theta_n = 0$, $\eta = 0.2$ and $\theta_{\text{jet}} = \{0, \pi/3\}$.

and

$$\begin{aligned} \bar{\omega}^2 &= \alpha + \alpha' + \alpha'' + \beta + \beta' + \beta'' + \gamma + \mathbf{k}^2, \\ \Omega &= \alpha + \alpha' + \alpha'' - \beta - \beta' - \beta'' + \gamma + \mathbf{k}^2. \end{aligned} \quad (26)$$

For real $\omega > |\mathbf{k}|$, the square root of Eq. (25) is always positive leading to two stable modes for G -modes.

We vary various parameters introduced earlier to find the solutions numerically. We, in Fig.1, plot the results for the stable A -mode with single jet and dijet for various parameters explained in the figure. For completeness we have also plotted the results when there is no jet. We see

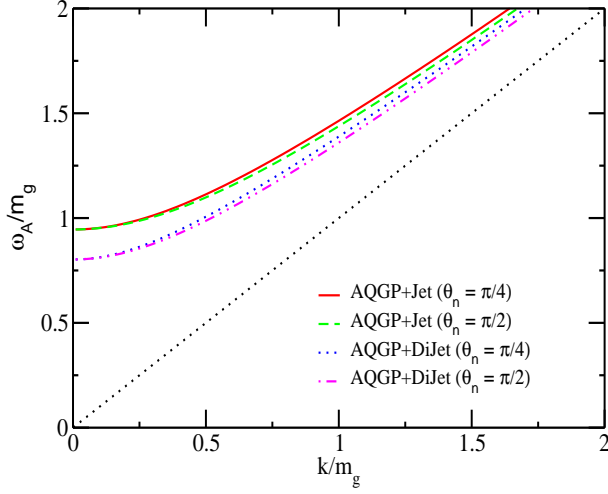


FIG. 3: (Color online) Same as Fig.2 for different values of $\theta_n = \{\pi/4, \pi/2\}$ and $\xi = 10$, $\theta_{jet} = 0$, $\eta = 0.2$ and $v_{jet} = 0.7$.

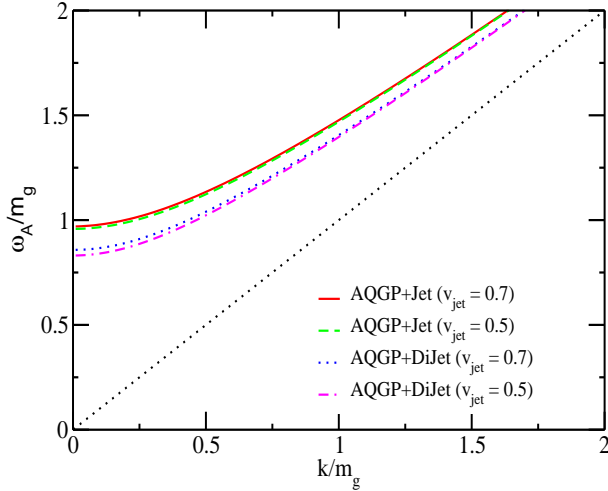


FIG. 4: (Color online) Same as Fig.2 for $\xi = 10$, $\theta_n = \pi/4$, $\theta_{jet} = \pi/3$, $\eta = 0.2$ and $v_{jet} = \{0.5, 0.7\}$

that the collective modes with the dijet differs reasonably from that with single jet and also with no jet. In order to see the dependence of the dispersion relation on the angle of propagation of the jet with the wave vector the results for the A -modes have been displayed in Fig.2 for $\xi = 10$, $v_{jet} = 0.7$, $\theta_n = 0$ and $\eta = 0.2$ where one can clearly see that the dispersion relation is sensitive to θ_{jet} . Next we consider the variation of the dispersion relations for A -modes with the anisotropy direction θ_n . For fixed θ_{jet} the results are in shown in Fig.3. The dispersion relation for dijet (jet) is not at all sensitive at low momentum and is marginally sensitive at higher momentum. The important thing is to notice that the dijet results for fixed θ_n substantially differ from that with the single jet. The sensitivity of the dispersion relation

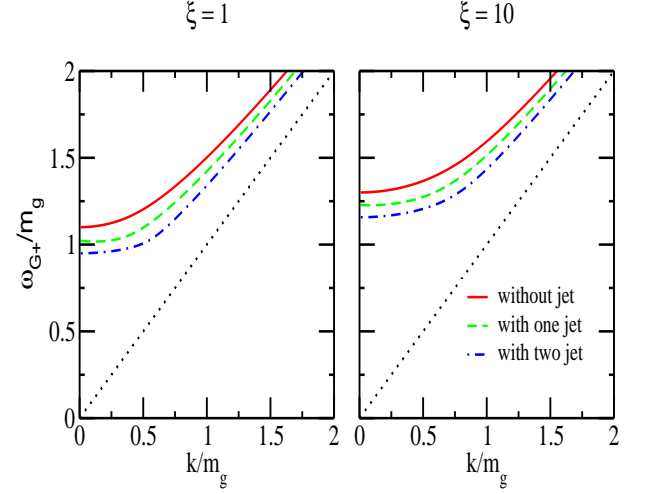


FIG. 5: (Color online) The dispersion relation for the stable G_+ -mode for an anisotropic plasma with jet for $\theta_n = \pi/4$, $\theta_{jet} = 0$, $\eta = 0.2$ and $v_{jet} = 0.7$. The left(right) panel corresponds to anisotropy parameter $\xi = 1(10)$.

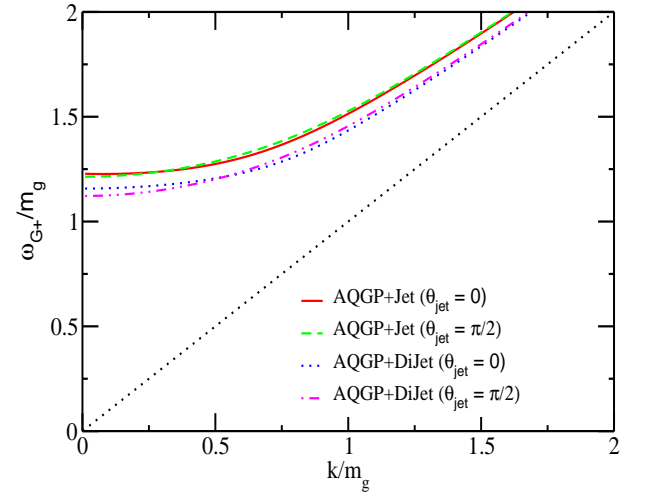


FIG. 6: (Color online) The dispersion relation for the stable G_+ -mode for the system composed of anisotropic plasma with single jet and dijet for $\xi = 10$, $v_{jet} = 0.7$, $\theta_n = \pi/4$, $\eta = 0.2$ and different $\theta_{jet} = \{0, \pi/2\}$.

for the stable A -modes on the jet velocity is displayed in Fig.4 for $\theta_n = \pi/4$. We see that the results changes marginally by varying the jet velocity both for single jet and dijet propagation.

It can be checked that γ and \tilde{n}^2 vanish identically when $\mathbf{k} \parallel \hat{\mathbf{n}}$. This leads to similar dispersion relations for G_+ -modes for $\theta_n = 0$. First of all, we display the results for G_+ -modes in Fig.5 for two values of the anisotropic parameter ξ . The results are quite sensitive to ξ for fixed θ_n . It is also seen that for fixed ξ and θ_n the dijet results differ substantially from the single jet case. We also find marginal dependence of G_+ -modes on θ_{jet} at

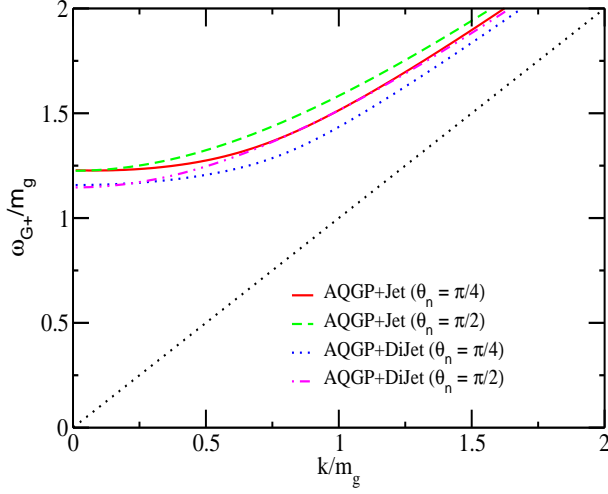


FIG. 7: (Color online) Same as Fig.6 for $\xi = 10$, $v_{jet} = 0.7$, $\theta_{jet} = 0$ and $\eta = 0.2$ and $\theta_n = \{\pi/4, \pi/2\}$.

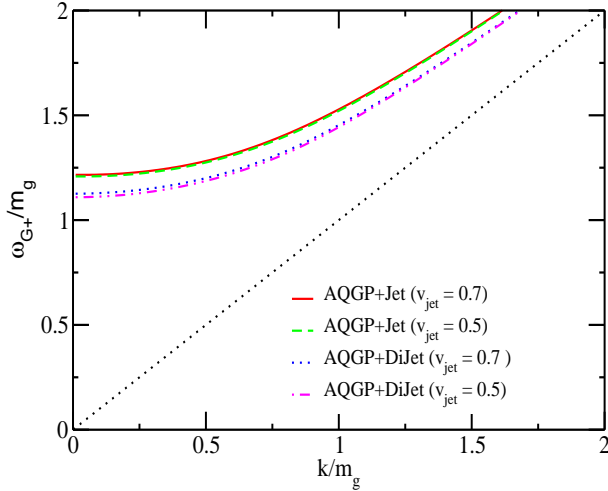


FIG. 8: (Color online) Same as Fig.6 for $\theta_n = \pi/4$, $\xi = 10$, $\eta = 0.2$, $\theta_{jet} = \pi/3$ and $v_{jet} = \{0.7, 0.5\}$.

very low momentum (see Fig.6). In Fig.7 the sensitivity of the dispersion relation of the G_+ -modes with the anisotropy direction (θ_n) has been displayed. It is found that the stable G_+ -modes are quite sensitive to θ_n . It is also observed that the dijet results are quite different from the single jet case which is an important finding in the present work. We have also found that as in the case of single jet, dijet results are not that sensitive to the jet velocity (see Fig.8). Finally, for stable modes, we consider the G_- -modes which have been shown in Fig.9 for $\xi = \{1, 10\}$, $\eta = 0.2$, $\theta_{jet} = 0$, $v_{jet} = 0.7$ and $\theta_n = \pi/4$ with and without jets. We find significant difference in the collective modes between single jet and dijet. The θ_{jet} -dependence of the G_- -modes for $\theta_{jet} = \{0, \pi/2\}$ is displayed in Fig.10. It is seen that the dispersion rela-

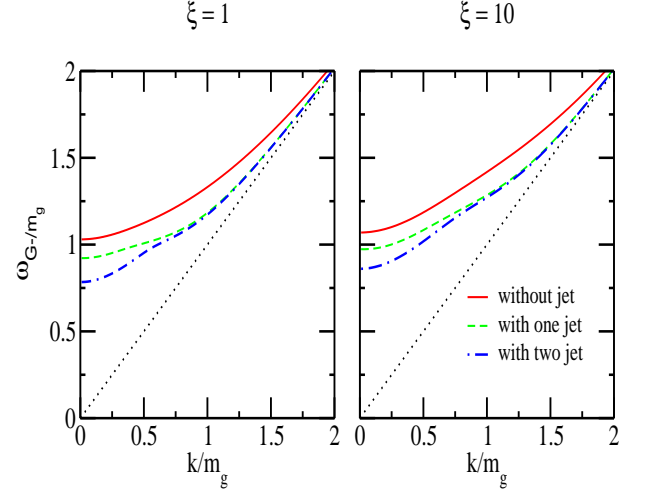


FIG. 9: (Color online) The dispersion relation for the stable G_- -mode for an anisotropy plasma and a jet for $\theta_n = \pi/4$, $\theta_{jet} = 0$, $v_{jet} = 0.7$ and $\eta = 0.2$. The left(right) panel corresponds to anisotropy parameter $\xi = 1(10)$.

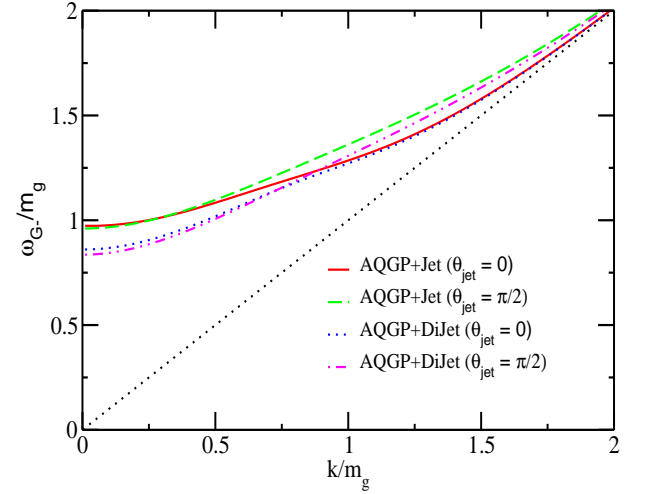


FIG. 10: (Color online) The dispersion relation for the stable $G_-(G)$ -mode for the composed of anisotropic plasma with single jet and dijet for $\theta_{jet} = \{0, \pi/2\}$, $\xi = 10$, $v_{jet} = 0.7$, $\theta_n = \pi/4$ and $\eta = 0.2$.

tion for G_- -mode is more sensitive to θ_{jet} which is not the case for A and G_+ -modes. The dispersion relation for G_- -modes for various θ_n is plotted in Fig.11. We find significant dependencies on θ_n . The collective mode for G_- -mode is also marginally sensitive to the jet velocity (see Fig.12).

B. Unstable modes

In the static limit, for small θ_n some of the scales appearing in the dispersion relations are negative implying

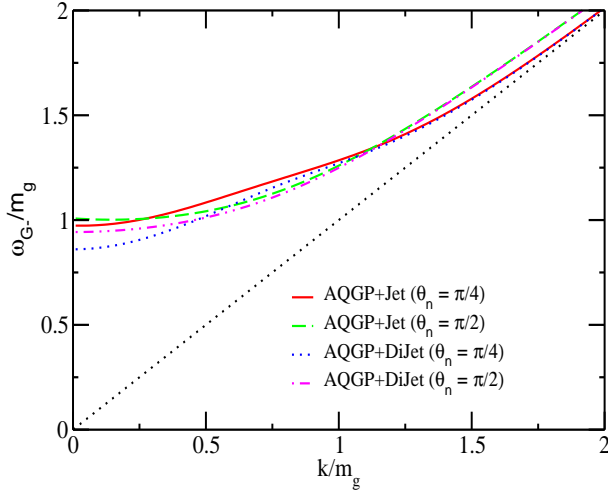


FIG. 11: (Color online) Same as Fig.10 for $\xi = 10$, $v_{jet} = 0.7$, $\theta_{jet} = 0$, $\eta = 0.2$ and different $\theta_n = \{\pi/4, \pi/2\}$.

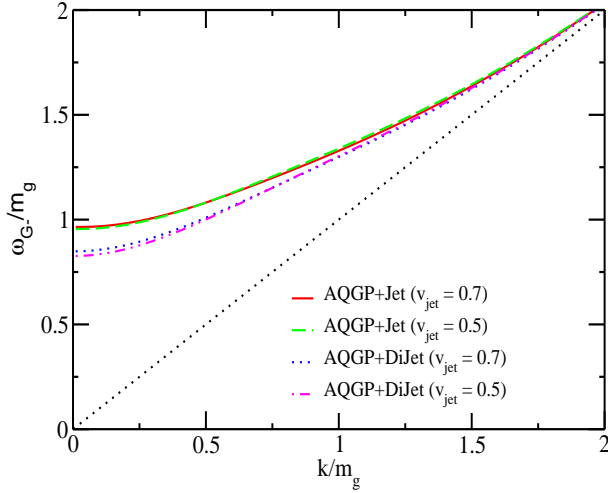


FIG. 12: (Color online) Same as Fig.10 for $\xi = 10$, $\theta_n = \pi/4$, $\theta_{jet} = \pi/3$, $\eta = 0.2$ and different $v_{jet} = \{0.7, 0.5\}$.

that the whole system is unstable with respect to magnetic instability [17, 18]. It has been demonstrated that in case of $\mathbf{k} \parallel \hat{\mathbf{n}}(\theta_n = 0)$, the growth rate of the filamentation instabilities is the largest [10, 11, 15]. In such case γ and \tilde{n}^2 vanish identically and the dispersion relations (henceforth called α and β modes) for the unstable modes simplify to

$$\omega^2 - \mathbf{k}^2 - \alpha(\omega) - \alpha'(\omega) - \alpha''(\omega) = 0 \quad (27)$$

$$\omega^2 - \beta(\omega) - \beta'(\omega) - \beta''(\omega) = 0 \quad (28)$$

In the numerical solutions of the above equations we have checked that unstable mode exists only for α mode both for single jet [4] and dijet. Let us now concentrate on the dispersion relations for the unstable α mode for which we shall, first assume that $\theta_{jet} = 0$. It is numerically checked

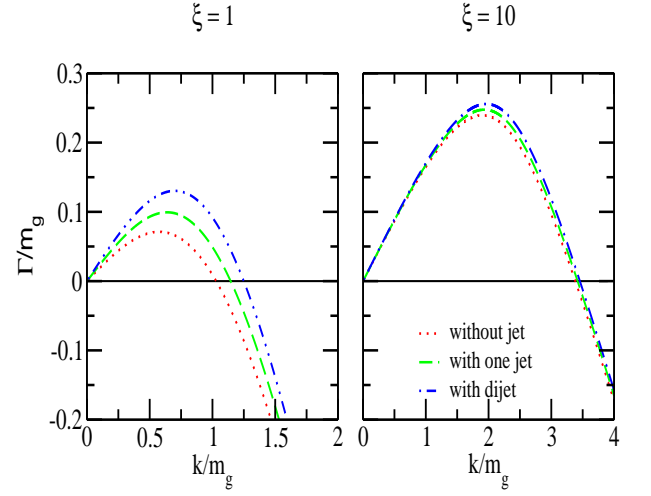


FIG. 13: (Color online) The growth rate Γ of the unstable mode of single jet and dijet for two different anisotropy parameter $\xi = \{1, 10\}$ and $\theta_{jet} = 0$, $\eta = 0.2$ and $v_{jet} = 0.7$.

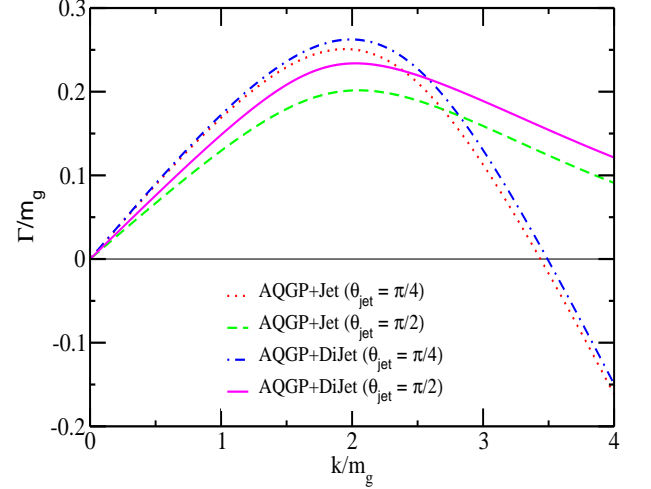


FIG. 14: (Color online) Same as Fig.13 with $\xi = 10$, $v_{jet} = 0.7$, $\eta = 0.2$ and $\theta_{jet} = \{\pi/4, \pi/2\}$.

that ω is purely imaginary, i.e. $\omega = i\Gamma$ with Γ real valued. We first show our results for two values of the anisotropy parameter $\xi = \{1, 10\}$ and for fixed values of the other parameters in the model. This is depicted in Fig.13. The growth of the instability in case of dijet is more compared to the single jet case for a fixed value of the anisotropy parameter. However, like the case of single jet results [4], the instability first increases and then becomes damped. It is also seen that the results are quite sensitive to ξ .

For $\theta_{jet} \neq 0$ the roots of the dispersion relations are of the form of $\omega = a + i\Gamma$, i. e. these are unstable propagating modes. This has been checked numerically. The results for the unstable modes with non-zero θ_{jet} is delineated in Fig.14. both for single jet and dijet. For

$\theta_{\text{jet}} = \pi/4$ the results are similar to the case of $\theta_{\text{jet}} = 0$. However, for $\theta_{\text{jet}} = \pi/2$, the instability always grows for dijet case as well as in the case of single jet which has already been reported [4]. In this case the modes never become damped. It is also worthwhile to note that the dijet induced instability for $\theta_n = \pi/2$ is more compared to the single jet case.

IV. SUMMARY

The dispersion relations of both stable and unstable collective modes in AQGP due to the dijet propagation have been obtained and solved numerically. We then compare it with that obtained in case of single jet and no jet cases. Depending upon the values of different parameters and for the dijet case considered here, the stable

modes differ significantly from that obtained with single jet. We have shown the dependencies of the dispersion relations (both for single and dijet) on various parameters explained in the text. It has been observed that the dispersion relation for stable modes are very sensitive to the anisotropy parameter, the anisotropy direction and the jet direction with respect to the wave vector. For the unstable modes it is found that the growth rate with dijet is more compared to the single jet case. In particular, for $\theta_{\text{jet}} = \pi/2$, the growth rate for the dijet case is substantially larger and it always grows like the single jet case [4]. Thus the introduction of dijet might lead to faster isotropization as compared to the single jet case. For the special case considered here ($\hat{\mathbf{k}} \parallel \hat{\mathbf{n}}$) no unstable modes exists for β -mode even with the dijet. However, more general case might lead to β -unstable modes which is worth investigating.

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